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A bibliometric analysis of climate change adaptation based on massive research literature data

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ABSTRACT

To clarify the current situation, hotspots, and development trends, in the field of climate change adaptation, we analysed a massive literature dataset from the Web of Science database by bibliometric method. By characterising the data about each publication, the result indicate that the field of climate change adaptation has entered a stage of rapid development. The USA occupies a leading position in terms of comprehensive strength with the largest publications output as well as a greater influence therewith. The most productive journal, author, and institution are Climatic Change, Ford JD from Canada, and The Chinese Academy of Science, respectively. Collaboration in this field continues to strengthen, but the growth rates at national levels are relatively low. In addition, the frequency and co-occurrence analysis of keywords reveals ten important research topics: climate change, adaptation, vulnerability, ecosystem, socio-economic system, agriculture, region, extreme event, mitigation, and sustainability, as the foci of climate change adaptation. “Vulnerability” is in a core position in all keywords with the strongest betweenness therein. The results of this work will help researchers clarify the current situation in climate change adaptation science but also provide guidance for future research.

1. Introduction

In recent years, climate change has had a more significant impact on earth's ecosystem and its human socio-economic system. In response to climate change, countries all over the world have enacted various policy measures to reduce greenhouse gas emissions to reduce the further rise in global average temperatures, and reduce the risks and losses of climate change. The fifth assessment report of the Intergovernmental Panel On Climate Change (IPCC) points out that, even were humans to cease their greenhouse gas emissions, many aspects of climate change and the related influence will last for several centuries (Pachauri et al., 2014), meaning that the impact of climate change in the short term has been “locked”, and it is difficult to reduce climate change and its impact through mitigation measures in the short-term. Therefore, no matter whether people make urgent efforts in reducing emissions, to cope with climate change risk, and weaken the existing adverse effects of climate change, adaptation is inevitable. Relative to mitigation measures, how to adapt to climate change in an active manner is a more realistic and pressing problem at present.

The definition of climate change adaptation has focussed the debate among researchers in the early days. Smit and Wandel (2006) reviewed the concept of human communities on climate change adaptation and revealed that human community adaptation is closely related to their adaptive capacity and vulnerability. Callaway et al. (1998) emphasized the adaptability of climate change should also include the direct influence of family and enterprises on climate change, and the behaviour adjustment of the direct influence of the means of production and product price changes caused by climate change, rather than be limited to a few specific projects designed to address climate change such as dams and breakwaters. With the extensive application of the method in the study of climate change, the definition of the fifth assessment report of the IPCC on climate adaptation has been widely accepted by researchers, which defined climate change adaptation as “the

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adjustment process in view of the actual or expected climate and its influence" (Ipcc, 2014). It is a complex process mutually crossed by different scales, (geography and time), different purposes (autonomy and plan), and different adaptation entities (natural systems and human systems, individual and collective endeavours, and areas and departments) (Adger et al., 2007). In recent years, a large number of research articles have covered extensive research and discussion on adaptation from various fields and dimensions. Lin et al. (2017) developed a precise community-scale energy system adaptation model to support the adaptive line planning of community energy system under uncertain conditions. Sussman et al. (2013) evaluated the size *status quo* of United States adaptation cost, showing that the USA's adaptation costs could reach tens of billions of dollars *per annum* by the middle of the 21st century. Some researchers have conducted comprehensive economic efficiency analysis on the climate change adaptation scheme for a specific wine region (Zhu et al., 2014). Fankhauser (2016) reviewed climate change adaptation problem analysis methods, discussed the economic agents' decision-making to address climate change risk, confirmed that adaptation could effectively reduce the risk imposed by climate change, but also highlighted the difficulties in effective adaptation, pointing out the necessity of taking various measures to cope with climate change and the importance of public policy in promoting healthy adaptation. Although the study of climate change adaptation is receiving more and more attention, the vast majority of studies focus on a specific direction or problem, and there are few articles about the overall development trend and research focus in the entire field of climate change adaptation.

Bibliometric analysis, as an important quantitative analysis tool, can effectively describe the overall trend of the development of a subject or field, and it has been widely used in various fields (De Bakker et al., 2016; Hirsch, 2005). In recent years, the bibliometric method is more and more frequently used in climate change research. Li et al. (2011) used it to evaluate the academic output, trends, features, and research methods in climate change literature from 1992 to 2009, and proposed a key innovative clustering analysis method. Wang et al. (2014) explored the development trend of the literature in the cognate area of climate change vulnerability through quantitative analysis, pointing out that health problems in the socio-economic system, food safety problems in agriculture, and water resources management problem were the most frequently discussed in the field of vulnerability research at present. Based on SCI -E and SSCI database, Wei et al. (2015) reviewed research hotspots and model methods used in the field of climate policy modelling with a bibliometric method. Janssen et al. (2006) conducted a literature measurement analysis on resilience, vulnerability, and adaptation of human activities in the face of global environmental change, and discussed their interrelationships.

It is essential to be able to describe the current research situation, hot topics, and future research trends in the field of climate change adaptation by surveying, and summarising, the literature; however, to the best of our knowledge there is little work that focuses on this problem. To contribute to filling the gap in the existing research, we conducted our work in the following ways: first, we applied the bibliometric method to analyse the current research situation and development trends, including the total numbers of publications, their geographical distribution, productive journals, authors and institutions, and most cited articles. In addition, the degree of academic collaboration and national comprehensive research strength were also measured and analysed. Second, to discover hot research topics in the field, word-clustering analysis, frequency analysis, co-occurrence, and network analyses were conducted on the high frequency keywords in this area. Finally, some suggestions and limitations regarding the climate change adaptation research are provided.

In summary, this work contributes to the current research in the following aspects: (1) we fill the blank in which no one is assessing the research trends in the field of climate change adaptation. (2) Using word-clustering analysis, frequency analysis, and co-occurrence analysis of keywords, the current hotspots in adaptation area are deduced, which will help other researchers grasp the nature of the more advanced topics in this cognate area. (3) Potential research directions and limitations are deduced according to the analytical results of this research, which will offer guidance to the planning and execution of future research.

2. Data and methodology

The data were collected from Web of Science Core Collection, including Science Citation Index Expanded, Social Sciences Citation Index, Conference Proceedings Citation Index – Science, Conference Proceedings Citation Index - Social Science & Humanities, Current Chemical Reactions, and so forth. The synonymous keywords of "climate change" and "adaptation" were determined using the method of reverse searching (Wang et al., 2014), and a total of 14,891 papers published from 1981 to 2016 were searched with TS (Topic) field which contains the title, abstract, keywords:

TS = (("climat* chang*" OR "global warm*" OR "environment* chang*" OR "global chang*" OR "climat* variability and change" OR "greenhouse gas" OR "greenhouse effect*" OR "carbon emission*") AND (adaptation OR adaptation OR adaptability)).

The retrieval date was 6 April 2017. The record includes the title, author, abstract, keywords, and references. According to previous studies (Yu et al., 2016; Zhang et al., 2016), this paper analyses the following indicators using bibliometric analysis software, such as Bibexcel.

General statistics, including the number of articles of different countries over time, geographical distribution, journals, subject, productive authors, productive institutions, citations, and so on. In addition, this paper also uses indicators such as impact factor, H-index, academic collaboration, and national comprehensive strength to reflect the current academic impact of each country and author. Based on the above analysis, the latest research status, and trends in climate change adaptation research, were analysed with the aim of helping researchers and policy-makers interested in this field understand the overall situation in the field of climate change adaptation, and provide relevant literature for them.

For the identification of research hot spots, the author-selected keywords summarise the theme of the article, reflecting the author's concerns, areas or methods, which is the concentration and essence of any body of literature. Frequency and cluster analysis of author keywords is an effective way in which to explore the trend and research hotspot in a field, and this has been widely used in the field of bibliometrics (Deng et al., 2017; Haunschild et al., 2016). Here, we discuss hot topics of climate change adaptation and the potential evolutionary trends of this field based on keyword frequency and co-occurrence analysis.

2.1. Impact factor and H-index

As the most common assessment tool in bibliometrics, impact factor and H-index are often used to evaluate the influence of journals, authors, institutions, and countries. The impact factor is an annual report by Dr Garfield who is a founder of the Institute for Scientific Information, which is published annually by the Journal Citation Reports. It is an important indicator of journal influence, academic quality, and essay quality that can be validated for journal

selection and evaluation of scientific research reference. It is defined as:

For any given year, the impact factor of a certain journal is the average number of citations gained by per paper published in that journal during the two preceding years.

The impact factor for this paper is found in the 2015 Journal Citation Reports.

The H-index proposed by Hirsch in 2005 is defined as:

A scientist has index H if H of his/her N_p papers have at least H citations each, and the other N_p–H papers have no more than H citations each.

The H-Index incorporates both the number of articles and citations into the evaluation criteria so it can measure the academic achievement of different authors in specific areas more accurately, and a higher H-index means greater academic impact. Furthermore, the H-index not only measures the impact of individual authors but also the institutional strengths of institutions and countries in specific disciplines (Molinari and Molinari, 2008). Therefore, in any bibliometric analysis, the H-index is an important evaluation parameter.

2.2. Academic collaboration

Good collaboration is an important guarantee of academic development. One of the most obvious characteristics is that the collaboration of scientific research at various levels or scopes is increasingly extensive (de Solla Price, 1963). The degree of academic collaboration is a common indicator used to measure the closeness of collaboration in scientific research (Wei et al., 2014). Here, we calculate the degree of academic collaboration in the field of climate change adaptation from three aspects: authors, institutions, and countries. The calculations are conducted using the following formulae (Wei et al., 2013):

Auctorial degrees of collaboration:

$$C_A = \frac{\sum_{i=1}^{N} \alpha_i}{N} \tag{1}$$

Institutional degrees of collaboration:

$$C_I = \frac{\sum_{i=1}^{N} \beta_i}{N} \tag{2}$$

National degrees of collaboration:

$$C_C = \frac{\sum_{i=1}^{N} \gamma_i}{N} \tag{3}$$

where C_A, C_I, and C_C are auctorial, institutional, and national degrees of collaboration, respectively; α_i, β_i, and γ_i are numbers of authors, institutions, and countries for each paper; and N is the total number of papers in this field.

2.3. Comprehensive strength

Academic scale, academic influence, and academic competitive strength can reflect the academic impact of a country (Yu et al., 2016). We selected eight indicators to assess national comprehensive research strength of one country: total number of articles, total number of citations, number of hot articles, number of hot article citations, number of highly-cited articles (TOP100), number of highly-cited articles' citations (TOP100), number of productive authors, and number of productive institutions. Standard scores of the eight indicators are calculated by the standard method and then summed to get the comprehensive score for each country, as follows:

$$T_{ij} = \frac{x_{ij} - \overline{x_{ij}}}{\sqrt{\frac{\sum_i \left(x_{ij} - \overline{x_j}\right)^2}{M}}} + 1 \tag{4}$$

$$T_i = \sum_j T_{ij} \tag{5}$$

where T_{ij} is the standard score of indicator j in country i; x_{ij} is the original score of indicator j in country i; $\overline{x_{ij}}$ is the average score thereof; T_i is the sum of the standard scores in country i; and M is the number of countries.

3. General statistics

3.1. Number of publications by country

The number of publications is an important indicator used to assess the development trend in a particular field, the number of documents from a given country in this field can reflect the country's research strength in this field to a certain extent. It can be seen from the statistical results, there are 14,891 documents retrieved from 152 countries or regions, it is important to note that in this study “UK” refers to England, Scotland, Wales, and Northern Ireland; “China” only refers to mainland China: documents from Hong Kong, Macao, and Taiwan are not included under China but are analysed as separate entities.

Fig. 1 shows the geographical distribution of published articles in this field. Different colours represent different numbers of documents in different geographic regions, the deeper colour represents the fact that more articles are published there. It can be seen from the diagram that, articles about climate change adaptation are mainly concentrated in the USA, UK, Australia, Canada, Germany, China, and other countries. The research strength of The Netherlands, France, Italy, Spain, and other countries is also prominent in this field (Table 1). Among them, the USA is the country with the largest number of publications. There is a total of 3282 articles published in the USA which accounts for 22.8% of the total number of articles. Second and third are the UKn and Australia with 9.37% and 8.15% of the total number of articles. Canada, Germany, and China follow in rank order. The top ten countries which have a total out accounting for 70% of the world's total document volume, are mainly developed countries: because these developed countries are all carbon emitters, they face greater pressure on emission reduction and the impact of climate change. The socio-economic level of these developed countries has reached a higher level and they are not willing to take as much responsibility for reducing emissions, so they have been more inclined to reduce the loss caused by climate change through adaptive, and policy, measures in recent years (Thomas and Twyman, 2005). China is the only developing country in the top ten because China is in a stage of rapid development and it is inevitable that more energy consumption and higher carbon emissions will be produced. Therefore, China attaches great importance to energy conservation and emission reduction and actively participates in climate change measures.

Fig. 2 shows the changing global trend, and that in major high-yield countries, in the field of climate change and adaptation with time. It can be seen from Fig. 2 that the numbers of articles in this field is growing rapidly over time and it is clearly divided into three

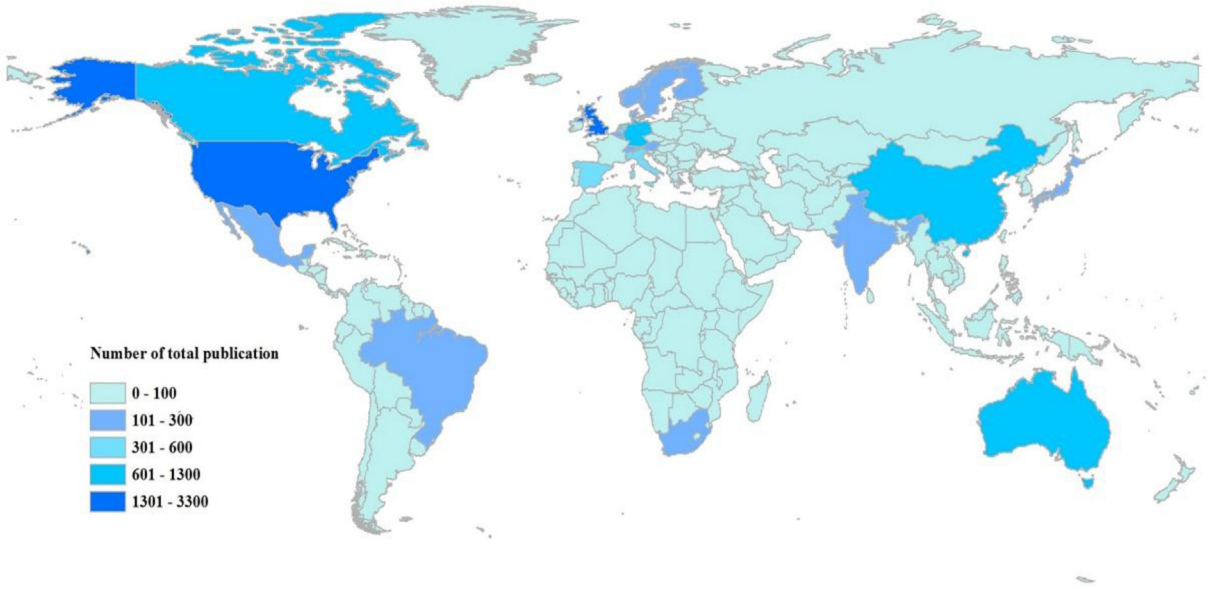

Fig. 1. Geographical distributions of publications, 1991–2016.

Table 1
Top 10 productive countries, 1991–2016.

Rank	Country	TP	TP R (%)
1	USA	3282	22.81%
2	UK	1349	9.37%
3	Australia	1173	8.15%
4	Canada	873	6.07%
5	Germany	842	5.85%
6	China	632	4.39%
7	Netherlands	541	3.76%
8	France	488	3.39%
9	Spain	414	2.88%
10	Italy	339	2.36%

Note: TP is the number of total publications; TP R(%) is the ratio of the number of one journal's publications to the total number of publications.

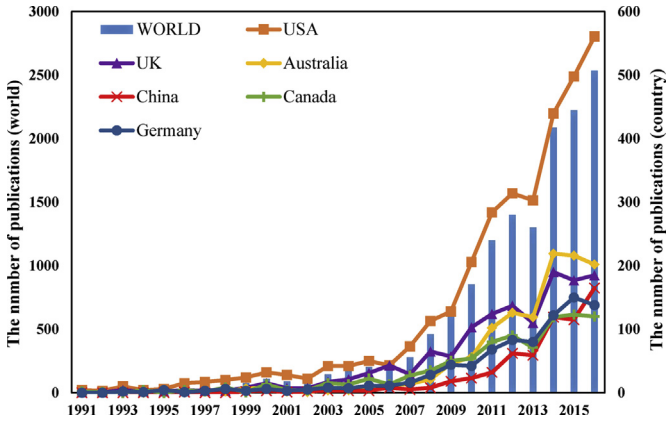

Fig. 2. Trends of climate change adaptation publications in main productive countries, 1991–2016.

stages: the first runs from 1991 to 1996, this stage is the early-start stage, the number of documents in the research field is relatively small in this stage, only a few developed countries such as the USA, and UK, published several articles. Although the world began to gradually focus on climate change and global warming and formulated the United Nations Framework Convention on Climate Change in 1992, except in a small number of developed countries, most countries, especially developing countries, are in a stage of rapid development, and there is no real attention paid to the effects of climate change. The second stage ran from 1997 to 2006, this was a stable stage of development. After the adoption of the Kyoto Protocol in 1997, many countries have begun to focus on and study the problems of climate change and global warming, but more research focuses on the measures and policies aimed at reducing emissions, so there is no significant increase in adaptation-related research. The third stage ran from 2007 to 2016, this stage was a rapid growth stage. With the deepening of the impact of climate change and the deepening of related research into climate change, people are becoming more aware of the importance of climate change, adaptation initiatives, and related studies. At 2007, Bali Road Map was adopted at United Nations Climate Conference. The Bali Road map emphasized the importance of adapting to climate change which had not got enough attention in the past global climate negotiations (Clémençon, 2008). As a result, the number of articles on climate change and adaptation grew rapidly. In the Copenhagen Accord, the document proposed that action and cooperation on adaptation especially in the least developed countries, small island countries, and Africa must pay "urgent" attention, which makes the number of publications have a significant increase since 2009.

3.2. Distribution of productive journals

Data were collected from 2125 academic journals in this field from the Web of Science kernel database. According to the analysis of those journals, the publications in the top 15 productive journals and their growth trends of publications over time are shown in Table 2 and Fig. 3. From Table 2, we can see that the journal distribution in this field is concentrated: the amount of articles in the listed 15 journals accounts for 21.44% of the total. Most of the study in the field of climate change adaptation can be found in the journals related to climate, environment, and ecology, with some journals categorised in biomedical sciences such as PLoS One and multidisciplinary entities such as PNAS paying attention to this field. Climatic Change was the most productive journals, as well as

Table 2
Top 15 productive journals, 1991–2016.

Rank	Journal	TP	TP R (%)	IF	TC	CPP
1	*Climatic Change*	564	3.92	3.34	12,569	22.29
2	*Global Environmental Change-Human and Policy Dimensions*	348	2.42	5.68	18,400	52.87
3	*PLoS One*	320	2.22	3.06	4058	12.68
4	*Regional Environmental Change*	260	1.81	2.66	2103	8.09
5	*Mitigation and Adaptation Strategies for Global Change*	202	1.40	3.09	2295	11.36
6	*Global Change Biology*	184	1.28	8.44	6159	33.47
7	*Environmental Science & Policy*	179	1.24	2.97	2976	16.63
8	*Ecology and Society*	156	1.08	2.89	1748	11.21
9	*Natural Hazards*	140	0.97	1.75	1300	9.29
10	*PNAS*	139	0.97	9.42	12,136	87.31
11	*Climate Research*	133	0.92	1.69	3507	26.37
12	*Climate and Development*	120	0.83	1.47	496	4.13
13	*Molecular Ecology*	120	0.83	5.95	2969	24.74
14	*Environmental Research Letters*	112	0.78	4.13	1589	14.19
15	*Nature Climate Change*	109	0.76	17.18	39,611	35.88

Note: TP is the number of total publications; TP R(%) is the ratio of the number of one journal's publications to the total number of publications; IF is impact factor in 2015; TC is the number of total citations; CPP is citations per publication.

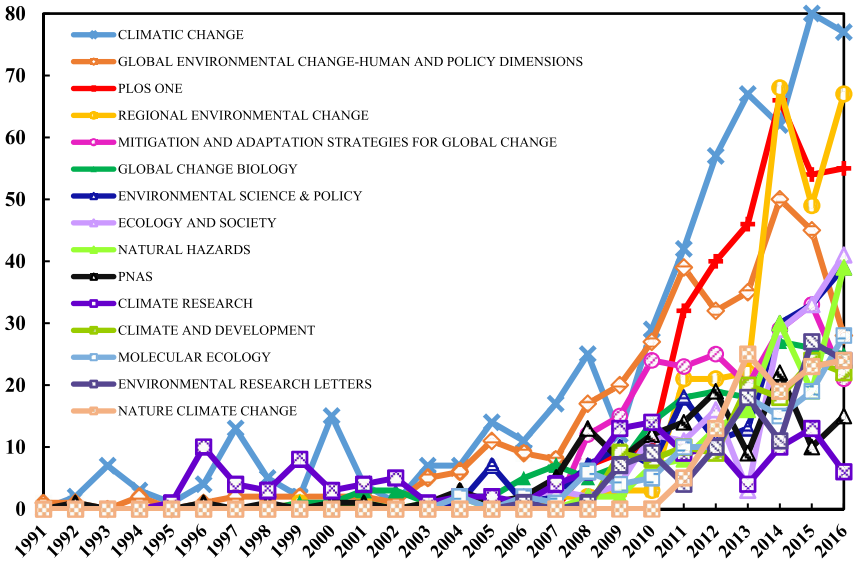

Fig. 3. Timeline of publications in the top 15 productive journals, 1991–2016.

one paying early attention to this field. It had published 564 articles related to this field by 2016 and accounted for 3.92% of the total. The second most productive journal was Global Environmental Change-Human and Policy Dimensions with 348 articles representing 2.42%, but this journal received the most citations of all journals, reaching 18,400 cites. PNAS ranked tenth of all publications in all the journals, but its citations per publication reached 87.31, ranked first in the listed top 15 productive journals. The total publications and citations from Nature Climate Change were relatively low, because of its late first issue, but the impact factor reached 17.18, ranked first in the top 15 productive journals. In the distribution of productive journals, the proportion of publications in this field is not high, which means that this field is distributed across extensive journals, and covers many research domains (Li et al., 2011).

From the trends of publications in various journals in Fig. 3, we can see that publications related to climate change adaptation grew rapidly from 2006, which was consistent with trends in national amounts of publications. Among these journals, Climatic Change published the most, maintained its lead in the number of publications in all stages from 1991 to 2016, in particular, after 2006, the publications in the field of climate change adaptation showed huge growth, with an average growth rate of 30.7% *per annum*. Publications related to climate change adaptation from PLoS ONE, Regional Environmental Change, *etc.* showed fluctuations in the short-term but maintained high growth rates. Meanwhile, publications related to this field from other journals showed relatively low growth rates.

3.3. Distribution of subjects

The contribution of the top 15 subjects in the field of climate change adaptation is listed in Table 3: Environmental Sciences & Ecology is the most popular subject with totally 6820 records, accounting for 47.39% of the total number, followed by Meteorology & Atmospheric Sciences and Science & Technology (other topics), with 11.76% and 7.68% respectively. Articles in this field mainly focused on natural science disciplines, especially environmental sciences, ecology, meteorology, and atmospheric sciences. There are few social sciences publications, and only one subject Business & Economics made the list, which showed that researchers were focusing more on climate change adaptation from the perspective of natural sciences. Some domain-specified subjects including

Table 3
Top 15 productive subjects, 1991–2016.

Rank	Subject	TP	TP R (%)
1	Environmental Sciences & Ecology	6820	47.39
2	Meteorology & Atmospheric Sciences	1692	11.76
3	Science & Technology - Other Topics	1105	7.68
4	Water Resources	1046	7.27
5	Agriculture	991	6.89
6	Geology	860	5.98
7	Evolutionary Biology	803	5.58
8	Geography	725	5.04
9	Engineering	698	4.85
10	Plant Sciences	654	4.54
11	Forestry	585	4.07
12	Biodiversity & Conservation	579	4.02
13	Genetics & Heredity	563	3.91
14	Marine & Freshwater Biology	555	3.86
15	Business & Economics	447	3.11

Note: TP is the number of total publications; TP R(%) is the ratio of the number of one subject's publications to the total number of publications.

Water Resource, Agriculture, Geography, and Evolutionary Biology also published numerous articles in this field of climate change adaptation because of their sensitivity to climate change, and the impacts thereof mainly occurred in these areas.

3.4. Analysis of productive authors

The quantity of an academic researcher's publication can reflect their research strength and the effectiveness of their work to some extent. Therefore, the number of papers published in a field is often regarded as an important index with which to weigh an author's influence in the field. According to the results of the search, 14,891 articles were written by 41,840 authors. Among them, the total number of authors with more than five articles, accounting for 3% of the total number, accounted for 14.3% of the total number of authors in the field. Table 4 lists the top 15 authors in the field of climate change: the biggest number of authors was from China. Four people from China and the other authors were from developed countries, such as Canada, the UK, Australia, or The Netherlands. There are two high-yield authors in these developed countries, once again showing that developed countries take the lead in the area of climate change adaptation.

The most productive author in this field is Ford JD from Canada, who has 43 articles. His articles are mainly about the relationship between climate and society, especially research into vulnerability and climate change adaptation (Ford and Smit, 2004; Ford et al., 2006). Adger WN, from the UK, has the highest total number of citations as an author: he has published 29 papers in the field, work that has been cited 4349 times, and the articles are cited nearly 150 times each. Adger WN is highest cited researcher in 2015, 2016, and 2017 in the social sciences. Among the 15 most cited articles in climate change adaptation field, Adger WN participated in four of them (three as first author, indicating his significant influence in this field). Nicholls RJ, also from the UK, has the highest H-index which reached 20, the most cited article analyses the global influence of sea level rise on degradation of flood risk and wetlands in coastal areas from regional and global perspective, points out that if you do not take measures to adapt, risk degradation in the 2080s in coastal regions and flood wetlands will increase greatly (Nicholls et al., 1999).

Table 4
Top 15 productive authors, 1991–2016.

Rank	Authors	Country	TP	TC	CPP	H-index
1	Ford JD	Canada	43	1121	26.07	18
2	Nicholls RJ	UK	39	1519	38.95	20
3	Ebi KL	Sweden	37	883	23.86	15
4	Wang J	China	35	312	8.91	12
5	Hoffmann AA	Australia	33	1613	48.88	16
6	Aerts JCJH	Netherlands	31	429	13.84	12
7	Li Y	China	29	452	15.59	9
7	Adger WN	UK	29	4349	149.97	17
9	Smit B	Canada	27	2450	90.74	19
10	Lobell DB	USA	26	2119	81.50	16
10	Tao FL	China	26	334	12.85	10
10	Iglesias A	Spain	26	514	19.77	13
13	Hobday AJ	Australia	25	374	14.96	10
13	Tol RSJ	Netherlands	25	1803	72.12	19
15	Zhang Z	China	24	417	17.38	10

Note: TP is the number of total publications; TC is the number of total citations; CPP is citations per publication.

3.5. Analysis of productive institutions

In terms of high-yield institutions, 14,891 articles from 8958 different research institutions are listed in Table 5: the top 15 research institutions published by the Chinese Academy of Science are listed in Table 5 In addition, other research institutions come from developed countries, of which four institutions came from Australia, three from the USA, UK, Canada, and The Netherlands, two from France, and one other also entered the top 15. We can see that the main research institutions in this field are concentrated in developed countries and the Research Institute national distribution is relatively wide, showing that adaptation to climate change issues draws attention from all over the world. Among the top 15 institutions, The Chinese Academy of Science has the largest number of research publications, with a total of 351 papers, accounting for 55.54% of the total number of Chinese publications, indicating that it occupies the leading position in the field of research in China. In other institutions, the H-index at the UK's University of East Anglia is as high as 53, ranked first in various research institutions.

3.6. Highly cited article analysis

The number of citations of scholarly articles reflects the academic impact of the essay in question. Of the 14,891 articles retrieved in this article, 395 were cited more than 100 times. Table 6 lists the 15 most-cited scholarly articles in the area of climate change adaptation at time of search. Among them, the USA and UK each have six articles, indicating that the academic achievements of researchers in both these countries have an extremely high influence in the field.

The most cited citation publication in this area was published in 2010 in Nature, written by RH Moss from the USA: *The next generation of scenarios for climate change research and assessment* (Moss et al., 2010). Total cites were 1523, with an average annual citation count of 217.57, showing its very high influence in this field. This article builds four different future emissions scenarios called “representative concentration pathways” (RCPs) that describe greenhouse gas emissions, atmospheric concentrations, air pollutant emissions, and land-use under different pathways, taking into account climate change Impact of Change Policies on Future Emissions. The RCP pathway provides input to climate change assessment models such as synthetic assessment models and is widely used in climate change impact and adaptive assessments and is included in the IPCC Fifth Assessment Report. Three of the top 15 articles were written by the first author, WN Adger from UK, of which the highest cited citations were *Vulnerability* published in Global Environmental Change-Human and Policy Dimensions in 2006, cited up to 1096 times. The article reviews the vulnerability

Table 5
Top 15 productive institutions, 1991–2016.

	Institution	Country	TP	TP RC (%)	TP RW (%)	H-index
1	Chinese Academy of Science	China	351	55.54	2.44	31
2	Wageningen University	Netherlands	208	38.45	1.45	30
3	The University of Queensland	Australia	192	16.37	1.33	31
4	University of Oxford	UK	189	14.01	1.31	39
5	University of British Columbia	Canada	186	21.31	1.29	37
6	Vrije Universiteit Amsterdam	Netherlands	168	31.05	1.17	37
7	The University of Melbourne	Australia	167	14.24	1.16	33
7	University of East Anglia	UK	167	12.38	1.09	53
9	The Australian National University	Australia	163	13.90	1.13	28
10	University of California, Davis	USA	153	4.66	1.06	34
11	Institut National de la Recherche Agronomique	France	151	30.94	1.05	31
12	James Cook University	Australia	148	12.62	1.03	29
13	University of Washington	USA	145	4.42	1.01	35
14	Stanford University	USA	143	4.36	0.99	43
15	McGill University	Canada	137	15.69	0.95	29

Table 6
Top 15 most frequently cited articles, 1991–2016.

Rank	Author	Year	Country	TC	CPY	Journal
1	Moss et al. (2010)	2010	USA	1523	217.57	*Nature*
2	Smit and Wandel (2006)	2006	Canada	1200	109.09	*Global Environmental Change-Human And Policy Dimensions*
3	Adger (2006)	2006	UK	1096	99.64	*Global Environmental Change-Human And Policy Dimensions*
4	Deutsch et al. (2008)	2008	USA	934	103.78	*Proceedings Of The National Academy Of Sciences Of The United States Of America*
5	Lobell et al. (2008)	2008	USA	814	90.44	*Science*
6	Tilman et al. (2011)	2011	USA	794	132.33	*Proceedings Of The National Academy Of Sciences Of The United States Of America*
7	Fowler et al. (2007)	2007	USA	782	78.20	*International Journal Of Climatology*
8	Kirkpatrick and Barton (1997)	1997	UK	681	34.05	*American Naturalist*
9	Neil Adger et al. (2005)	2005	UK	620	51.67	*Global Environmental Change-Human And Policy Dimensions*
10	Stainforth et al. (2005)	2005	UK	591	49.25	*Nature*
11	Gruhler et al. (2005)	2005	Denmark	580	48.33	*Molecular & Cellular Proteomics*
12	Pörtner (2002)	2002	Germany	579	38.60	*Comparative Biochemistry And Physiology A-molecular And Integrative Physiology*
13	Millar et al. (2007)	2007	USA	576	57.60	*Ecological Applications*
14	Adger (2003)	2003	UK	507	36.21	*Economic Geography*
15	Brooks et al. (2005).	2005	UK	503	41.92	*Global Environmental Change-Human And Policy Dimensions*

Note: TC is the number of total citations of this article; CPY means citation per year.

studies of environmental change and discusses the challenges it faces in helping people the better to study resilience and adaptation (Adger, 2006). The other two articles, cited 620 and 507 times, demonstrate the author's prominent influence in the area of climate change adaptation.

3.7. Comprehensive strength analysis

We calculated the ranking of comprehensive research strength of each country in the field of climate change adaptation according to formulae (4) and (5), as shown in Fig. 4: the indicators and the total standard score (TSS) of the USA are much higher than those of other countries, with a TSS of 28.23 points; each indicator for the UK remained at a high level, with total standard scores of 12.69 ranking it in second place. For Australia, the scores of the three indices of PA, TH, and THC are relatively high, and the total standard score is 10.45, ranking it third. As the only developing country in the top ten, China's total standard score is 3.38, ranking it eighth. The USA and China are representatives of developed and developing countries, respectively. In terms of the value of standard scores, the USA's scores are far higher than China's, showing its strong research strength; however, the contribution of different indicators to the comprehensive strength of the USA and China is different. For the USA, the highest standard score of all indicators is PI, while the highest standard score for China is PA, indicating that the overall strength of the USA is largely expressed by the research output of its institutions, while China expressed its influence through the output of individual authors. Moreover, compared with

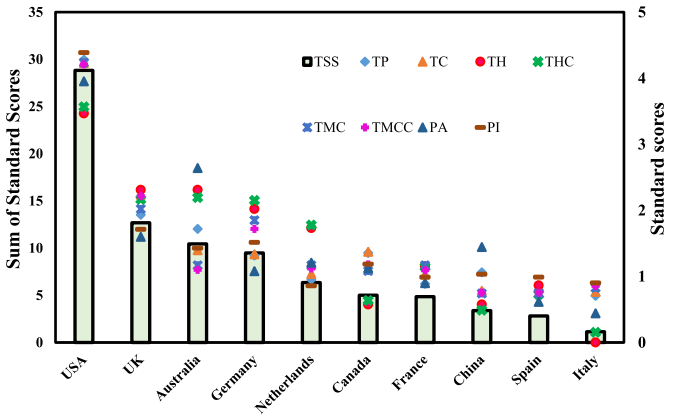

Fig. 4. The national comprehensive strength in climate change adaptation, 1991–2016.

China, the contribution of TMC to the comprehensive score of the USA is higher than that of China, indicating that China still needs to improve its influence in terms of output of high-level papers.

Note: TP is the total number of publications; TC is the total number of citations; TH is the total number of hot articles; THC is the total number of citations of hot articles; TMC is the total number of the most cited articles; TMCC is the total number of the most cited articles' citations; PA is the number of productive authors; PI is the number of productive institutions; and TSS is the total standard score.

3.8. Academic collaboration

As the negative effects of climate change on socio-economic systems continue to increase, the problem of adaptation to climate change is becoming a complex scientific issue, which needs different authors, institutions, and countries to cooperate and collaborate. The degree of academic collaboration can reflect the closeness of scientific research in the field of climate change and the degree of academic research in this field. Here we calculate the degree of collaboration among authors, agencies, and countries according to formulae (1) to (3):

As shown in Fig. 5, the degree of collaboration at all levels is rising and author collaboration is more obvious, reaching 4.7 and the level of institutional collaboration has risen steadily, reaching 2.9 in 2016, suggesting that more and more authors and institutions in the field of climate change adaptation tend to collaborate on research.

The growth in national collaboration is relatively slow since climate change adaptation issues in individual regions or countries are now more focused. The three levels of collaboration (author, institution, and country) collaboration are 4.18, 2.51, and 1.58 respectively, means that per articles, 4.18 authors, 2.51 institutions, and 1.58 countries were involved in its writing.

4. Research hotpoints

4.1. Keyword clustering and frequency analysis

Keywords, which reflect the authors' intentions and interests, summarise the key content of a paper, therefore, the frequency analysis of keywords is key to investigating hot topics and developments associated with a field. Here we summarised 25,301 keywords used in 14,891 papers by means of BibExcel software: the keyword “Climate Change” with 4230 appearances, has the highest frequency of use. In bibliometrics, Price's Law is generally used to estimate the outputs and influence of the authors. Similarly, it can be also employed to determine the lowest frequency of core keywords. According to the formula $n = 0.749 \times \sqrt{m_{max}}$, where m_{max} denotes the citations of the keywords which are most frequently cited (Allison et al., 1976; de Solla Price, 1963), we found that $n = 49$, which implies that the keywords which are cited over 49 times, are at the core of the cognate area. We summarised 89 core keywords. By further arrangement, we classified the core keywords with high frequency, and the 10 highest keywords in terms of number of citations are shown in Table 7.

4.1.1. Climate change

From Table 7, it can be found that “Climate change” is a classification of keywords with the highest frequency, implying that climate change has become increasingly important. Due to the excess emission of the greenhouse gas, the global climate has significantly changed, which leads to serious impacts on the nature-society-economy system. In the context of the “Kyoto Protocol” and “Paris climate agreement”, to confront the impact and economic loss caused by climate change, the people have conducted much research with respect to mitigation of, and adaptation to, climate change. In particular, the adaptation to the adverse effects which have been caused by climate change, and its prevention in the future (Bowen et al., 2011), have been increasingly of concern to scholars and governments worldwide.

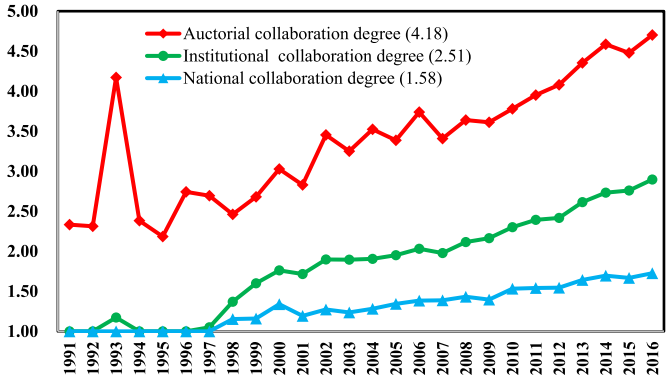

Fig. 5. Three levels of collaboration degrees, 1992–2016.

4.1.2. Adaptation

Without doubt, adaptation is also one of the classifications of the keywords with high frequency. In fact, the influence caused by the climate change is inevitable. While employing different means to mitigate greenhouse gas emissions to prevent the increase in global average temperature, how to adapt the effects of climate change on natural, and socio-economic, systems by adaptive actions, adjusting and managing human activities, and sufficient use of beneficial factors, has been the focus of the academia. According to Table 7, in the classification of adaptation, climate change adaptation (Hunt and Watkiss, 2010), resilience (Nelson et al., 2007), adaptive capacity (Lutz and Muttarak, 2017), and local adaptation (Savolainen et al., 2013) are key foci.

4.1.3. Vulnerability

The keyword “vulnerability”, which refers to the propensity or predisposition to be adversely affected, plays an important role in the study of adaptation. From the perspective of the IPCC report, the vulnerability of natural and social systems largely determines the risk of climate change (IPCC, 2013). As a result, among the keywords with respects to vulnerability, the keywords related to risk often appear. Meanwhile, the estimation of vulnerability in the study of the adaptation to climate change is conducive to choice of proper adaptation measures to reduce the vulnerability of systems or individuals, which is meaningful in terms of mitigating the risk of climate change. Due to the complex relationship between climate change and the inherent vulnerability of humans, society, and the ecosystem, there is much uncertainty with respect to the estimation of vulnerability (Berkhout et al., 2014). As a result, how to deal with the endogenetic uncertainty, is also a concerned shared by some scholars.

4.1.4. Ecosystem

In relation to the socio-economic system, the natural ecosystem is more sensitive to the influences of climate change. At present, climate change has been one of the main factors to threaten both the ecosystem and biodiversity. Phenotypic plasticity is the most used keyword in the classification of an ecosystem, since individuals with the same genes in an ecosystem, will form different phenotype behaviours, physiologies, or formations to adapt to environmental change, such as the increase of temperature, *etc*. The study of phenotypic plasticity is conducive to researchers better understanding how biological individuals in an ecosystem adapt to climate change. Meanwhile, other keywords (phenology, biodiversity, ecosystem services, *etc*.), also attract considerable attention.

4.1.5. Socio-economic system

Climate change is a serious challenge for the sustainable development of the entire socio-economic system, for instance, the rise in sea level and desertification of land caused by climate change results in mass migrations (Brzoska and Fröhlich, 2016) and

Table 7
Frequency of keywords in climate change adaptation research.

Category	Representative keywords	Frequency of keywords
Climate change	*Climate change(4230), Global warming(285), Temperature(266), Climate(143), Global change(132), Environmental change(123), Climate variability(113), Climate change impacts(83)*	5375
Adaptation	*Adaptation(2525), Climate change adaptation(463), Resilience(422), Adaptive capacity(298), Local adaptation(211), Climate adaptation(170), Adaptive management(77), Acclimation(73), Adaptation strategies(68), Thermal adaptation(49)*	4356
Vulnerability	*Vulnerability(613), Uncertainty(184), Risk(113), Impacts(89), Vulnerability assessment(65), Risk management(62), Risk assessment(55), Disaster risk reduction(54), Perception(53), Risk perception(52)*	1340
Ecosystem	*Phenotypic plasticity(203), Phenology(149), Biodiversity(111), Ecosystem services(91), Evolution(86), Natural selection(72), Genetic diversity(68), Plasticity(65), Photosynthesis(62), Genetic variation(58)*	1342
Socialeconomical system	*Governance(162), Migration(127), Development(94), Policy(79), Livelihoods(74), Health(67), Institutions(67), Climate policy(64), Land use(55), Planning(55)*	942
Agriculture	*Agriculture(289), food security(173), Irrigation(73), Maize(54)*	589
Region	*China(90), Australia(87), Africa(84), Bangladesh(71), Arctic(71), India(66), Canada(62), Europe(54)*	585
Extreme event	*Drought(258), Flooding/Floods/Flood(186), Heat stress(63), Extinction(51)*	558
Mitigation	*Mitigation(250)*	250
Sustainability	*Sustainability(145), Sustainable development(95)*	240

Note: Numbers in parentheses represent the frequency of occurrences of representative keywords respectively.

replanning of the use of land (Duguma et al., 2014). To adapt to the influence caused by climate change, it is important to establish proper management mechanisms to coordinate the relationship between socio-economic development and adaptation to climate change (van Buuren et al., 2014), and choose and formulate proper climate policy, which is also one of the hot topics in the field of adaptation to climate change.

4.1.6. Other topics

According to Table 7, the other hot keywords in the field of adaptation of climate change also include agriculture, region, extreme event, mitigation, sustainability, *etc*. In general, agriculture is one of the sectors which is most sensitive to the climate change, and how to confront the changes in crop yield (Lychuk et al., 2017), food safety (Rasul and Sharma, 2015) and so on by adaptation measures, has attracted the attention of many researchers. As the regional limitation of the study of the adaptation to climate change, the region is also a classification of keywords with high frequency. Among them, China has the highest frequency thereof, which implies that China is intensely concerned about this field, however, increasing climate change will lead to the rapid increase in occurrence of extreme climate events, for instance, droughts, floods, heat waves, *etc*., and influence those regions and sectors sensitive to climate change (Bréda et al., 2006) (Nicholls et al., 1999). Therefore, it deserves further discussion as to how to reduce the loss and influence caused by extreme climate events by proper measures. With respect to mitigation, researchers paid more attention to how to balance, mitigate, and adapt the relationships to maximally reduce the influence of climate change (Parry, 2009).

4.2. Co-occurrence and network analysis of keywords

Here, we selected high-frequency keywords which occurred more than 49 times to make a co-occurrence analysis of keywords based on the VOSviewer software. We deleted the two most common keywords in case they affected the display of other keywords. The co-occurrence map of keywords of climate change adaptation area is shown in Fig. 6. Each keyword is represented by a circle, where the diameter of the circle and size of its label represent the number of links between the keyword and the other. The bigger the circle, the more links the keywords have. The proximity of a circle to another indicates the degree of relatedness of the two keywords (Haunschild et al., 2016), and its colour represents the average publication year of keywords which is shown in the colour bar. Lines, the more frequently the two keywords occur together, the thicker the line between them is, represent the co-occurrence links

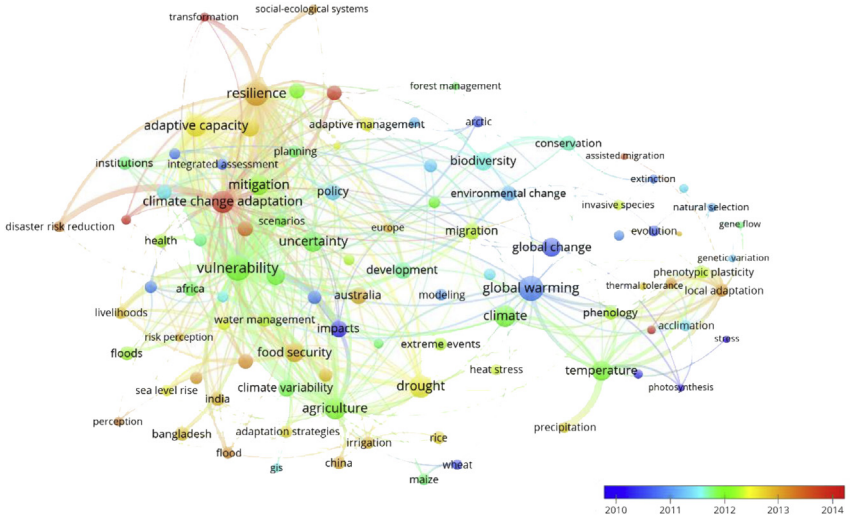

Fig. 6. The occurrence network map of keywords of climate change adaptation area.

between two keywords. As seen from Fig. 6, vulnerability has the most links with other keywords because it was the most common. It means that vulnerability has the biggest betweenness which reflects its core position in the study (White and Borgatti, 1994). Keywords of relatively large size, such as climate change adaptation, resilience, adaptive capacity, global warming, and agriculture, also hold an important position in the research network. Among all these keywords, the lines between vulnerability, adaptive capacity, and resilience are thickest which means that these three keywords, or two of them, often appear together in the same publication. This feature shows that the strongest relevance was between vulnerability, adaptive capacity, and resilience, and most researchers study around these issues. Other keyword groups such as climate change adaptation and vulnerability, temperature and precipitation, vulnerability and agriculture also exhibit a strong occurrence relevance which implies that all of these combinations are foci for climate change adaptation work. The difference between the colours of keyword reflects the hot issues in a different year. Through the change of colour, we can figure out the change of the hot topics in this field in recent years. In the blue colour which represents publishing time before 2010, most keywords like “global warming”, “impact”, “evolution”, “biodiversity” etc. mainly focus on the impacts of global warming on ecosystems and how the ecosphere adapt the global change. As the global average temperature rises, the impacts of climate change are more and more serious, and the researchers are increasingly focusing on the vulnerability and uncertainty assessment in different emission scenarios and different temperature threshold around 2012, which are represented by green colour. As the most climate-sensitive sector, agriculture has received extensive attention in the field of adaptation at this period. Then, around 2014, more and more researches are focusing on some specific topics and regions including “food security”, “drought”, “China”, “Australia”, “local adaptation” etc. rather than abstract and macroscopic topics, and more and more social science problem such as “social-ecological systems”, “adaptive management”, “perception” and so on has been concerned. All these trends above represent that the hot topic in the field of climate change adaptation is changing from natural science to social science, from macro-level to regional level.

5. Conclusion

Based on the Web of Science core database, a detailed analysis was conducted of the overall development conditions of climate change adaptation areas of research from 1981 to 2016 through use of a bibliometric method. The key conclusions are as follows:

The field of climate change adaptation has developed rapidly since 2006 with the number of publications increasing at an average growth rate of 29.06% *per annum*. The number of publications continued to increase, showing that climate change adaptation is a burgeoning topic, and is receiving more and more attention. At a country-level, developed countries, especially the USA, hold key leadership positions in terms of comprehensive strength with the largest numbers of publications as well as a greater academic influence. As a representative of the world's developing countries, China returned a good performance in terms of high-yield institutions and authors, but there is remained a gap between China and other top developed countries. The top five most productive journals contributed 21.44% of all publications in this field in which the most productive journal was Climatic Change, while there was a wide distribution of articles published in many different journals. In addition, climate change adaptation is a multidisciplinary field because the articles covered 127 subjects, and Environmental Sciences and Ecology, Meteorology & Atmospheric Sciences, and Science & Technology - Other topics, were the top three categories that saw the publication of the most papers. In this area, Ford JD and Nicholls RJ were the most prolific authors, although Adger WN (from the UK) published fewer papers, his achievements were more widely cited and exerted a significant influence in the field. Academic collaboration show an up-trend at auctorial, institutional, and national levels with average degrees of collaboration of 4.18, 2.51, and 1.58, respectively.

The clustering analysis and frequency analysis of the keyword shows that the hot topic categories in the field of climate change adaptation can mainly be found in 10 categories such as: climate change, adaptation, vulnerability, ecosystem, socio-economic system, agriculture, region, extreme event, mitigation, and sustainability. Based on the occurrence analysis, “vulnerability” had the strongest betweenness of all keywords, reflecting the fact that “vulnerability” is the core issue in this area and it often appeared with other keywords at the same time. Through the analysis of keywords published in recent years, this paper also explores the changing trends of hot topics which researchers concern in the area of climate change adaptation. We find that the focuses are moving from natural science issue such as adaptation of ecosystem to environmental change, to social science issues like the risk management and adaptation of social public and socio-economic system to climate change. Comprehensive understanding of the future vulnerabilities, adaptive ability and resilience of interconnected human and natural systems remain challenges. Thus, more and more research has begun to focus on social, economic and cultural factors that interact with each other. At the same time, more and more recent studies focus on the specific micro problems, fields and regions to carry out quantitative analysis, but in the past, most works are qualitative analysis from a macro perspective. The conclusions of this study will help researchers to master the development of, and trends in, climate change adaptation research, and provide guidance and reference for future research in this field.

During the study, however, we found that there were some limitations in this study to be solved in future work: the complexity of analysing authors from different countries, regions and organisation names poses a significant difficulty in any statistical analysis; the statistics pertaining to the corresponding number of published papers may not be entirely accurate. Since some countries such as the UK consist of several parts, they may be repeatedly counted. (2) Along with the continuous renewal of papers in the database, the results of this study, such as a number of published papers, and citation rates will change over time, and as such can never represent the latest results. (3) To identify future research directions, in addition to the literature metrology described here, it is deemed necessary to undertake a more detailed literature review around the most interesting current research topics and methods in the field of climate change.

Note: TP is the number of total publications; TP RC (%) is the percentage of the total number of the institution to that of its country; TP RW (%) is the percentage of the total number of the institution to that of the world.

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